Chapter 12

HSDPA Indoor Planning

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12.1 Introduction

This chapter introduces principles of indoor coverage and capacity planning, concentrating on requirements created by High-Speed Downlink Access (HSDPA) service. The basic principles and elements for planning Universal Mobile Telecommunication System (UMTS) indoor network using wideband code division multiple access (WCDMA) are presented, and two different basic configurations to provide HSDPA service inside buildings are further investigated. In a dedicated indoor system, the service is provided by a dedicated indoor base station that is connected to an antenna system inside the building. The other approach uses a WCDMA repeater that amplifies the received signal from the outdoor UMTS network to the indoor antenna system. The superiority of dedicated indoor systems, as well as outdoor-to-indoor repeaters compared to a traditional macrocellular approach is clearly shown in the literature (e.g., [9,10]). The Release 99 (R99) specification defines the basis of the UMTS system, and the Release 5 (R5) introduces the HSDPA bringing improvements mostly to the physical layer and radio resource control [3,7]. The fundamentals of HSDPA are not discussed here but can be studied in the literature (e.g., [4,7]). This chapter introduces the basics of WCDMA indoor planning, emphasizing the requirements that HSDPA has brought out.

The first section starts with a description of the indoor radio propagation environment and the challenges it causes to WCDMA systems. Then, “Strategies and Configurations for Providing Indoor Coverage” continues by introducing different strategies for providing dedicated cellular HSDPA service to indoor locations from the network functionality point of view, and presents different system configurations. Then the “Equipment” section presents the essential technical properties of the equipment used in implementing the UMTS indoor network. In “HSDPA Indoor Network Planning,” the planning process for HSDPA indoor system is assessed. Example link

budgets for different UMTS/HSDPA indoor configurations are presented, the capacity of HSDPA in indoor radio channel is analyzed, and different aspects of optimizing the performance of indoor HSDPA service are discussed.

12.2 Indoor Environment and Propagation

12.2.1 Indoor Propagation Channel

The radio propagation channel describes what kind of changes the transmitted signal is undergoing while propagating through the environment. The propagation environment types can be roughly categorized into macro- and microcellular outdoor environments and picocellular indoor environment. The basic parameters that characterize the propagation environment are

- Delay profile or delay spread
- Frequency response
- Coherence bandwidth
- Angular spread
- Doppler spread
- Propagation slope
- Location variability or slow-fading standard deviation

Indoor delay profiles clearly differ from outdoor environments. Delay spread in different outdoor environments can vary between 500 and 3000 ns [13], whereas in an indoor environment, the variation is between 10 and 500 ns [5,13]. In addition, the number of multipath components is typically higher indoors. Channel frequency response describes how different frequencies fade in the radio channel, and the coherence bandwidth defines the frequency range where fading correlates. Delay spread and coherence bandwidth have a direct relation:

$$\Delta f_c = \frac{1}{2\pi S} \tag{12.1}$$

where Δf_c is the coherence bandwidth and S is the delay spread of the channel. The coherence bandwidth in outdoor environments varies between 50 kHz and 1.6 MHz, whereas indoors it can vary from 300 kHz up to even larger than 16 MHz [13,20]. The angular spread in outdoor environments is a couple of tens of degrees in the horizontal, and below 10° in the vertical direction, whereas indoors it is typical to have an angular spread of 360° in both the vertical and horizontal direction. The Doppler spread is caused by movement of the transmitter, receiver, or propagation environment. In indoor environments, the Doppler spread is typically rather narrow

due to low mobile speed. Location variability, also known as slow fading standard deviation, has values between 4 and 8 dB outdoors, whereas indoors values of up to 10 dB have been reported [20]. Due to high wall and floor penetration loss, the typical propagation slope is clearly higher indoors. Finally, it can be concluded that the indoor propagation channel is quite different from the outdoor propagation channel.

12.2.2 Repeater Donor Link Propagation Channel

When considering utilization of outdoor-to-indoor repeater implementation, the donor antenna of the repeater is typically located on the roof of the building. Furthermore, the type of link between the repeater and the outdoor macro base station is considered a fixed point-to-point radio link. Obstacles in the repeater link would cause additional attenuation in the received power. For point-to-point radio links, the Fresnel zone should be left empty in order to avoid the additional attenuations in the link [20]. For a 2-GHz carrier frequency and 500-m link length, for example, the maximum radius of the Fresnel ellipsoid is approximately 4 m [20]. Based on the assumption of the non-obstructed link, the radio channel in the repeater donor side can be modeled using Friis' equation for free space radio propagation.

12.2.3 UMTS System Performance in an Indoor Environment

The bandwidth of a system, B, and the coherence bandwidth of the channel define whether a system is wideband or narrowband. In a narrowband system, the coherence bandwidth is larger than the system bandwidth; thus the whole system bandwidth fades simultaneously and the channel is flat fading. In a wideband system, the coherence bandwidth is clearly smaller than the system bandwidth; thus the channel is frequency selective (Table 12.1). So, in a wideband system, the average changes in the channel over the system bandwidth are clearly smaller compared to a narrowband system. According to Table 12.1 and Δf_c values shown above UMTS can be identified as wideband in all outdoor environments, but is changing toward narrowband in indoor environments, which may cause deterioration of system behavior.

A RAKE receiver in UMTS/WCDMA can mitigate multipath fading with maximal ratio combining. A typical receiver has a time resolution of one chip time (1/3.84 Mcps = 0.26 μs), which equals 78 meters in distance in air interface. Thus the receiver can separate multipath components that have more than one chip time separation. In indoor environments, the multipath components may have significantly shorter separations, which makes combining impossible, and therefore may degrade system performance.

Table 12.1 Definition of Narrowband and Wideband Systems.

Condition	*System*
$B \ll \Delta f_c$	Narrowband
$B \gg \Delta f_c$	Wideband

Source: From M.K. Simon and M.S. Alouini. Digital Communications over Fading Channels: A Unified Approach to Performance Analysis. Wiley InterScience, Sep 2000.

In WCDMA, different downlink channels from one base station are separated by synchronized orthogonal Walsh codes [6]. If the codes are fully orthogonal in the reception end, then the transmissions do not interfere with each other. However, in practice, the orthogonality is degraded due to multipath fading. The orthogonality varies as a function of multipath profile (delay spread) and distance, having values between 0 and 1, where 1 means perfect orthogonality. Longer delay spread and distance degrade the orthogonality, so indoor systems are expected to have better performance in terms of orthogonality [16]. Reported orthogonality values in dedicated indoor systems vary between 0.68 and 0.85; and when indoor coverage is provided by a macro cell, the orthogonality varies between 0.34 and 0.55 [10,21]. However, based on [16], larger variations may also occur. The results clearly indicate that dedicated indoor systems should provide better performance compared to indoor coverage from outdoor cells. The impact of changes in code orthogonality on HSDPA link- and system-level performance have been studied (e.g., [6,7]).

12.2.4 Indoor Propagation Areas

The different characteristics of indoor environments compared to outdoor environments are caused by very densely spaced obstacles in the environment. Furthermore, antennas are typically placed close to objects. Indoor environments can be categorized in many different ways, based on the usage, traffic, shape, material, etc. [5,8,20,21]. The different indoor environments have different characteristics: the propagation slope, number of scatterers and reflections, probability of line-of-sight, etc. In particular, the attenuation between floors and walls, and the number of windows can have a significant impact on signal propagation. In practice, indoor areas can be divided into a few basic categories:

- Dense areas (e.g., multiple small offices connected with narrow corridors)
- Corridors (e.g., long and wide corridors in buildings)

- Open areas (e.g., entry halls, auditoriums, airports, railway stations)
- Special areas (e.g., elevators, fire escapes, basements)

Different indoor areas have different propagation characteristics. An extensive list of references is provided in [5]; but because there is lots of variation, depending on the individual building, field measurements are recommended if accurate and reliable propagation characteristics of a certain building are needed.

12.3 Strategies and Configurations for Providing Indoor Coverage

The most basic way of providing indoor coverage is to rely on outdoor cellular networks. However, building penetration attenuates the signal typically by 15 to 20 dB. This requires large thresholds in link budget. Thus, either indoor coverage is not available on the cell edge, or large cell overlapping is needed, which increases other cell interference levels. For the inner parts of larger buildings, the attenuation may be clearly higher, and thus lack of coverage is probable. In the case of power-controlled R99 connections, indoor users with high path loss cause excess downlink interference to outdoor users, whereas with HSDPA, indoor users are expected to have poor throughput. Because it is probable to have the users requiring high throughput located indoors, improving indoor coverage may be worthwhile for network operators.

There are two basic approaches to improve indoor coverage: a dedicated indoor system and an outdoor-to-indoor repeater. When considering the cell configuration, there are two strategies: using a single cell for one building or having multiple cells in one building. In addition, the antenna configuration can use a single antenna at a cell, or a distributed antenna system (DAS) where the signal is split to several antennas or radiating cables. In the future, different optical solutions are likely to replace lossy coaxial cables, where antennas would be replaced by remote RF (radio frequency) heads, including optical interfaces, amplifiers, and antennas.

12.3.1 Single-Cell Strategy

In single-cell strategy (Figure 12.1(a)), a building is covered using one indoor cell or one outdoor-to-indoor repeater. Heavy exterior walls are blocking the signals from outdoor cells, there are no handover regions inside buildings, and also the other cell interference remains at low level. Varying numbers of antennas can be connected to the base station. A single antenna may be built into the base station, whereas distributed antenna

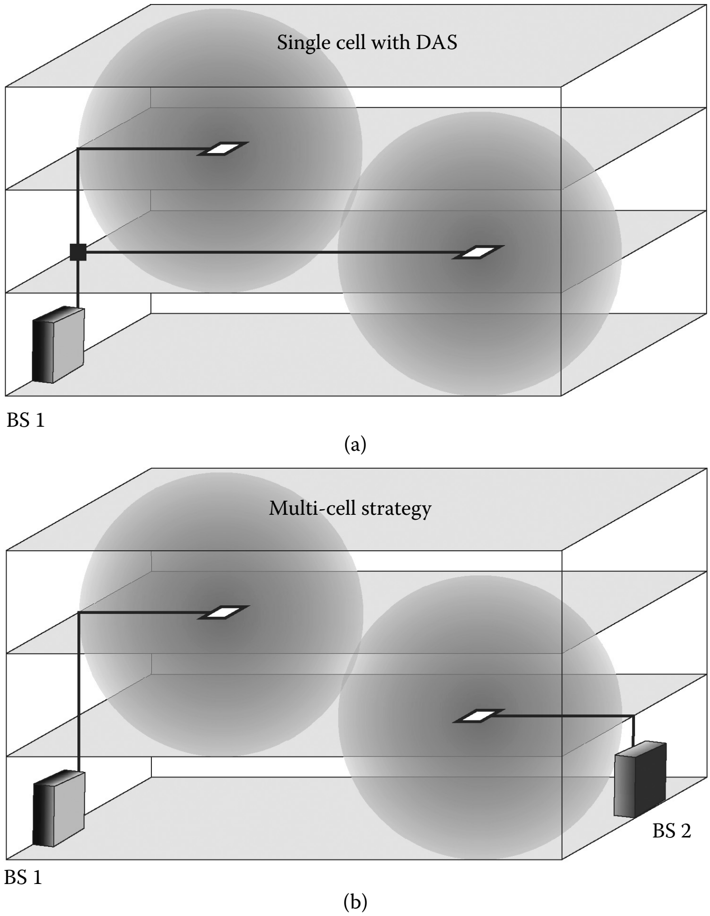

Figure 12.1 Principal difference between (a) single-cell strategy implemented using multiple antennas, and (b) multi-cell strategy.

systems may have tens of antennas. Although a DAS with several antennas can be used in the single-cell strategy to cover even larger buildings, the cell size cannot be endlessly increased, due to increasing antenna line losses. Also, the total available capacity is limited to one cell. Thus, the single-cell strategy is well suited for small buildings, or medium-sized buildings with low amounts of traffic.

12.3.2 Multi-Cell Strategy

For larger buildings with high numbers of users, the multi-cell strategy (Figure 12.1(b)) can be considered. In a multi-cell strategy, the indoor

coverage is formed by several adjacent indoor cells, which creates handover regions inside the building. Therefore, the antenna locations must be more carefully selected due to the handovers taking place when a user moves between the cells. Due to slow fading variations in the received signal level, some overlapping between the cells is needed to guarantee continuous coverage. On the other hand, other cell interference must be efficiently controlled. Therefore, in a multi-cell strategy, antenna selection and placement must be done more carefully than in the single-cell strategy.

Because the cost of the multi-cell indoor network is high, the network can be deployed in parts. An outdoor-to-indoor repeater can be used as a first solution to ensure coverage. Later, it can be upgraded to a dedicated indoor system utilizing an indoor base station. As the capacity need grows, a multi-cell indoor system can be deployed. If this is taken into account at the beginning, the indoor antenna installations can remain untouched throughout the network evolution.

12.3.3 Picocells and Femtocells

So-called pico or femto base stations are base stations with small power and in-built antenna, with an option to connect external antennas. The physical size of the base station is small enough to be mounted on an indoor wall similar to antennas. Femto base stations are even planned to be userdeployable, in a similar manner to that of wireless access points.

12.3.4 Distributed Antenna System (DAS)

The most used strategy for planning indoor is the distributed antenna system, where several antennas are connected to a single base station. The idea of DAS is to divide the signal from the base station into several branches, and to connect a discrete antenna or radiating cable to each branch. Typically, coaxial cables with signal dividers (splitters and tappers) are used, but also, for example, optical connection between Node B and active RF-heads can be used. Due to a steep propagation slope in indoor environments, the longitudinal loss in cables is lower than in an air interface. Thus, it is beneficial to split the signal into multiple antennas. DAS also brings users closer to the antenna, which shortens the propagation path, thus improving orthogonality due to less multipath fading and a higher probability of line-of-sight connection. Usually in DAS installation, diversity reception or low noise amplifiers (LNAs) are not used due to high cost [13]. The basic idea of DAS is illustrated in Figure 12.1(a) and an example layout is shown in Figure 12.3(a). In the sense of interference and functionality, a single-cell configuration outperforms a multi-cell configuration, because all antennas are connected to one Node B. Thus, the interference from other cells remains rather small, and handovers do not occur when users are moving in the building.

12.3.5 Outdoor-to-Indoor Repeater

If indoor base stations are not the preferred solution, and if sufficient outdoor networks are available, outdoor-to-indoor repeaters may be considered. A WCDMA repeater can be used to amplify the WCDMA signal between a nearby macrocellular outdoor base station and an indoor antenna system. When the receiving antenna of the repeater is placed on the rooftop of the building, and the received and amplified signal is guided to the indoor antennas using a cable, the signal does not need to penetrate through the exterior walls of the building. Therefore, the building penetration loss can be bypassed. Finally, the amplified WCDMA signal can be received by the indoor users without using an expensive indoor base station. This outdoor-to-indoor repeating principle can be utilized in practice to provide low-cost HSDPA service in a building located near the edge of an outdoor macro cell. Because additional signal amplification takes place at the repeater, data throughput can be increased due to an improved signal-to-interference ratio. The link between the repeater and the macrocellular base station is called the "donor link." Furthermore, the link between the indoor antenna and the indoor user is called "service link," and antennas are called "donor antennas" and "service antennas," correspondingly. In outdoor-to-indoor repeater implementation, the donor antenna connects the repeater to the macrocellular base station, while the serving indoor antenna system is connected to the repeater to provide service for indoor users. The outdoor-to-indoor repeating principle, together with an example repeater configuration, is illustrated in Figure 12.2.

The WCDMA repeater discussed in this chapter is an analog, transparent, nonregenerative repeater. This means that the repeater device does not utilize any signaling and control information from the network, but only

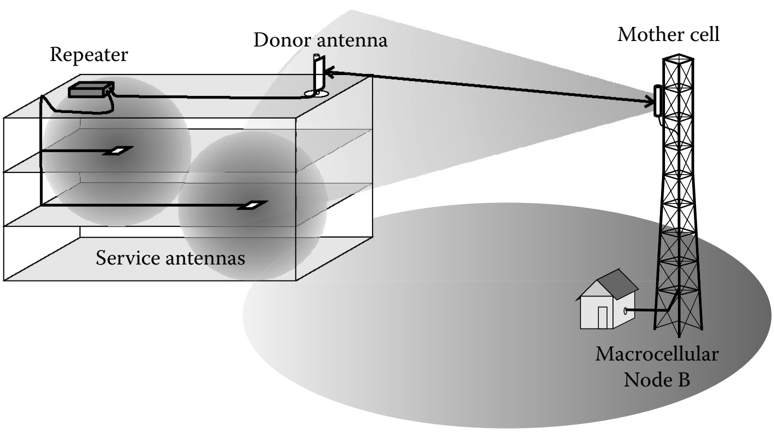

Figure 12.2 The principle of outdoor-to-indoor repeating.

repeats the entire desired carrier frequency band. Similarly, the network is not aware of the repeater's presence. The transparency of the repeater provides flexibility and cost efficiency. To deploy a repeater, no changes or reconfigurations are required on the network side. In addition, the cost of the repeater is low due to reduced device complexity, especially compared to a base station. Furthermore, the structural complexity of the radio network remains at the original level if a repeater is deployed instead of an indoor base station. For each new indoor base station, a connection to the radio network controller is required, which increases the structural complexity of the network. In the case of a repeater, this connection is not needed, and the existing capacity can be boosted with the existing radio resources. Because with a repeater the radio access interface is shared between the repeater users and the users of the mother cell (i.e., the cell to which the repeater is connected), repeater installation must be done with care to avoid decreasing the performance of the mother cell. The most important repeater-related parameters are repeater amplifier gain and repeater antenna deployment strategy. These planning-related parameters are further discussed later in this chapter.

12.4 Equipment

12.4.1 Antennas and Antenna Line Elements

12.4.1.1 Antenna Types

A typical indoor antenna is a small, low-gain antenna. Reasons for this are the wide angular spread in the indoor environment, coupling loss limitations when users are close to the antenna, and the need for invisible antenna installation. There are three basic types of indoor antennas: omnidirectional antennas, directional antennas, and radiating cables.

Omnidirectional antennas are typically used in an open area, such as a lobby or auditorium. The radiation pattern of an omnidirectional antenna is isotropic in the horizontal plane, and the vertical pattern is close to the ideal dipole antenna pattern; thus, the gain is approximately 2 dBi.

Directional indoor antennas are good for covering narrower areas, such as corridors. The radiation pattern is clearly wider than in directional macro cell antennas. Both the horizontal and vertical −3 dB beam width are around 70° to 90°, and the antenna gain is around 6 or 7 dBi.

Radiating cables (also called leaky feeders or coaxial antennas) can be used to provide smooth coverage for long distances. They are traditionally used in tunnels but can be used, for example, in elevator shafts, staircases, and corridors. Radiating cable is a special coaxial cable that has holes or a groove in the outer conductor and operates as a small antenna, leaking signal out from the cable.

Typical antennas for outdoor micro- and macrocellular networks can be also used at the donor side The antennas have about a 65° to 90° horizontal beam width for three-sectored, and 33° for six-sectored installations. The vertical beam width is typically between 6° and 12°. The antenna gain values are between 12 and 18 dBi. In some cases, even narrower antennas with higher gain can be considered.

12.4.1.2 Splitters and Tappers

Splitters and tappers are power dividers, and are needed in distributed antenna systems. A splitter divides the input power into equal parts, and typically has two to four ports, thus having an attenuation of 3 to 6 dB. A tapper divides the power into unequal parts, and typically has two ports, with attenuations of, for example, 1.0 and 7.0 dB, or 0.1 and 15 dB [9, 11].

12.4.1.3 Cables

Feeder cables in cellular networks are coaxial cables of between $\frac{1}{4}$ and $2\frac{1}{4}$ inch, and the attenuations at 2 GHz vary from 21 to 3.5 dB/100 m, respectively. Typical choices for micro- and macrocellular outdoor installations is $\frac{7}{8}$-inch cable with attenuation of about 6 dB/100 m; whereas in indoor installations, $\frac{1}{2}$-inch cable with attenuation of about 11 dB/100 m is a typical choice [11, 19].

More information about antenna line equipment, antenna patterns, specifications, etc. can be obtained from the manufacturers.

12.4.2 Base Station Equipment

The base station in UMTS is called Node B. Node B equipment has few indoor radio planning-related parameters, such as total transmission power and noise figure, and several radio resource control-related parameters, such as maximum power per user, pilot channel and other common channel powers, power allocated for HSDPA users, etc. Typically, macrocellular base stations have a maximum total transmission power of +43 to +50 dBm, and indoor base stations below +38 dBm. Path loss estimation is based on the primary common pilot channel (P-CPICH). Thus, the power setting of the pilot channel is an important parameter from the system performance point of view. The typical pilot channel power for a macro base station is +33 dBm, and for an indoor base station +27 to +30 dBm. In the case of a pico base station, power can be smaller than +27 dBm, and with femto base station, the total power can go down to +15 dBm.

The HSDPA power settings can be configured in various ways. Usually, R99 connections and HSDPA connections share the frequency. Thus, either a fixed part of the total power is reserved for HSDPA, or all the unused power can be allocated to HSDPA. In all configurations, a fixed amount

of power must be reserved for common channels, for example, the pilot channel. If a dedicated carrier for HSDPA is used, all the power remaining from the common channels can be utilized for the HSDPA users. The actual power allocation depends on each implementation, wherein the network vendor can set some limits. The impact of power allocation on HSDPA capacity is discussed in detail in [7].

12.4.3 WCDMA Repeaters

A WCDMA repeater is a device used to amplify and retransmit the received WCDMA signal on the same carrier frequency. Here, only analog and transparent repeaters are discussed; they operate at the physical layer and are unable to reduce the noise from the received signal.

A WCDMA repeater has two connectors for connecting the donor and service antennas. Naturally, power must be supplied to the amplifier from a power source. The configuration of the repeater setting is typically made by a computer using a local or remote connection.

12.4.3.1 Parameters

The most important repeater parameters are carrier frequency or channel number selection, and repeater amplifier gain for the uplink and downlink. The repeater amplifier gain affects the reception level of the signals in the uplink and downlink receiver, and is important from a network planning point of view. The repeater amplifier gain can typically have values between 50 dB and 90 dB.

12.4.3.2 Antenna Isolation

To guarantee successful repeater operation, the donor and service antennas must maintain sufficient isolation to prevent self-oscillation. In a self-oscillating state, the repeater starts to transmit the signal received and amplified by itself. This leads to uncontrollable repeater operation, and the mother cell will be blocked due to excess interference from the repeater. Based on [1], antenna isolation should maintain a level of 15 dB larger than the selected repeater amplifier gain. The antenna isolation is equal to the total attenuation measured between the donor and service antenna ports in the repeater. The isolation can be improved by adding attenuation between the donor and service antennas, by, for example, taking advantage of obstacles in the propagation environment, or by increasing the distance between the donor and service antennas of the repeater.

12.4.3.3 Automatic Gain Control

WCDMA repeaters typically include an automatic gain control system (AGC) to keep the output power of the repeater at a decent level in order to avoid

amplifier circuit oscillation due to antenna isolation problems. Thus, when setting the repeater amplifier gain, it is important to check whether or not the AGC has been activated. If AGC is active, the set repeater amplifier gain may not actually be the one used by the repeater.

12.4.3.4 Noise

Noise produced in repeater circuits plays a crucial role in repeater planning because the noise is amplified by the repeater along with the desired signal. Thus, the required repeater amplifier gain is directly proportional to the amount of noise received at the target locations (base station receiver and mobile station receiver). This is discussed in more detail later. The noise is composed of thermal noise and of impairments of the repeater device. The addition of noise caused by the repeater device impairments can be modeled using a noise figure. The noise figure of the repeater is typically 2 dB to 4 dB.

12.4.3.5 Power

A repeater amplifier has a maximum characteristic output power for the uplink and downlink. This sets the maximum average power level measured at the output ports of the repeater. According to [1], a typical value for the maximum average output power is +30 dBm in the downlink direction. With strong input signals at the repeater, the maximum average power level may start to limit the output signal level.

12.5 HSDPA Indoor Network Planning

The planning process of a WCDMA radio network is divided into dimensioning, detailed planning, and optimization. The detailed planning is further divided into configuration planning, combined coverage and capacity planning called topology planning, code planning, and parameter planning [13]. The basic guidelines used in an outdoor network planning process can be adapted to the planning of indoor networks. The main differences lie in the configuration planning and topology planning phases. In the configuration planning phase, the antenna line elements are defined and the link budget calculations are performed. The topology planning of an outdoor network is based on coverage predictions and system simulations. Due to lower reliability in propagation prediction indoors, system simulations are providing only a rough indication of system coverage and performance, while the detailed planning is more empirical and experiential.

The target of indoor planning is to design the indoor network in such a way that adequate signal quality can be ensured in the targeted indoor location. In planning a dedicated indoor system, the main challenge is to

find good parameters in the base station to provide proper coverage and capacity. However, for the outdoor-to-indoor repeater solution, repeater parameters also have a direct impact on the mother cell. Thus, the surrounding macrocellular network must be considered when deploying the repeater.

The actual placement of the antennas needs careful planning. Sufficient signal levels must be provided in all important areas to ensure the required service coverage. A sufficient signal level is defined by planning thresholds, which are based on link budget calculations, system simulations, and radio interface measurements. Controlling the leakage of outdoor signal inside the building, as well as leakage of indoor signal outside the building is important in handling inter-cell interference, as well as smooth handovers. Because HSDPA does not support soft handover (SHO), large cell overlapping is inadvisable. In probable handover areas to outdoor network, such as main entrances, indoor coverage can be slightly extended to the outdoors in a controlled way to ensure successful handovers. Inside the building, the coverage provided by the indoor system should be planned in such a way that handovers to outdoor networks do not occur. Controlling the indoor coverate is especially challenging near windows, which are areas prone to signal leakage between outdoor and indoor networks. Furthermore, the indoor network should not cause excess interference to the outdoor network operating in the same frequency band. Tinted outermost windows in new buildings help in isolating outdoor and indoor networks.

Indoor planning tools with propagation models can be used in dimensioning the network, but field measurements with test transmitters are recommended to verify the characteristics of the environment.

12.5.1 Planning of Dedicated UMTS Indoor System with DAS

The basic target of planning a DAS is to provide constant coverage everywhere in the building. Typically this is best achieved by having equal effective isotropic radiated power (EIRP) at each antenna. Because it is usually impossible to keep equal cable loss for each antenna, splitters and tappers must be smartly used to keep the antenna EIRP values in balance. In the example configuration in Figure 12.3, the maximum difference between the antenna line losses to different antennas is 1.6 dB, although cable losses vary significantly. The selection of the antenna depends on the indoor area type. For open area, an omnidirectional antenna is a typical selection. On the other hand, a directional antenna may be a better fit for a corridor environment [13]. Due to its complicated installation, 1/2-inch cable is a typical selection, although the longitudinal loss is rather high [21]. Because users may be located very close to antennas in an indoor environment, it is important to take care of coupling loss (the loss between a Node B antenna connector and the mobile station antenna). If the coupling loss is

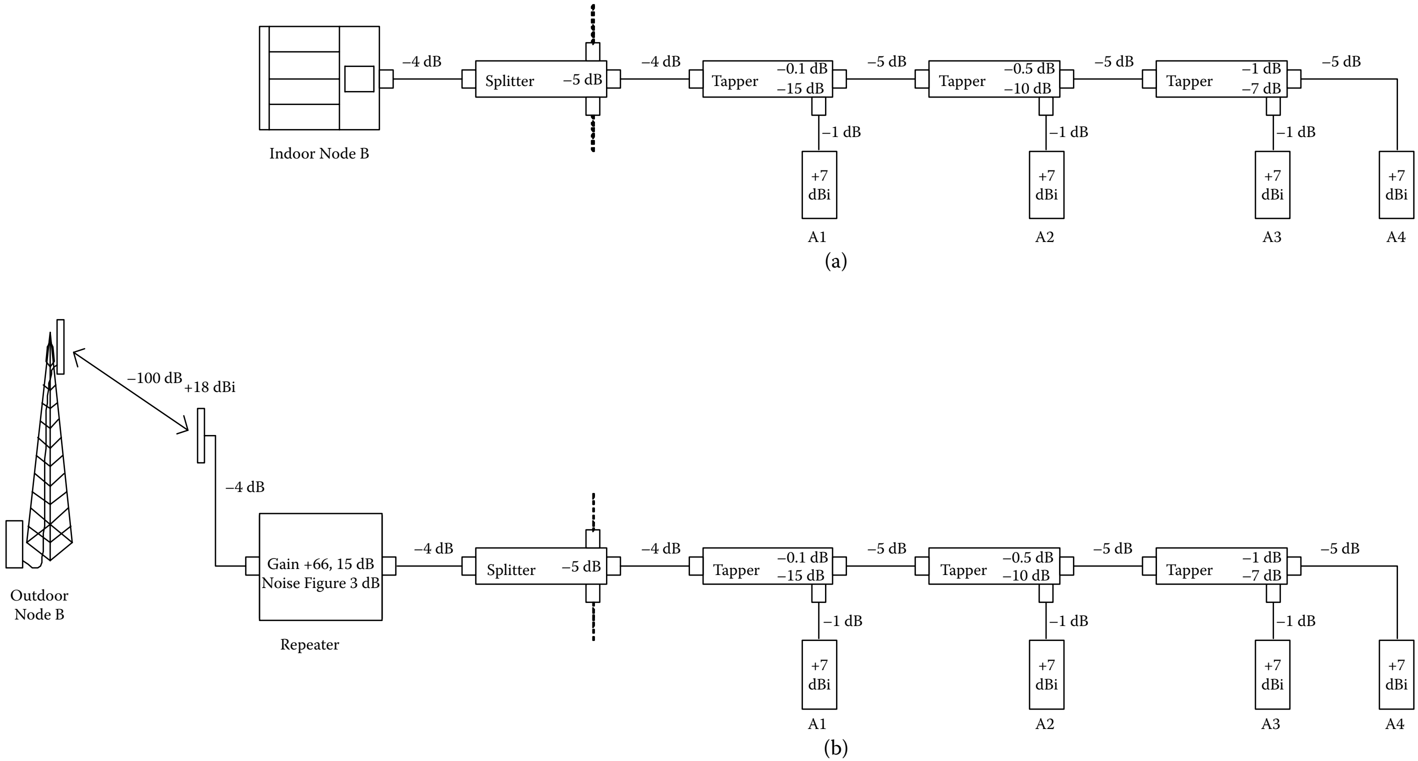

Figure 12.3 Example DAS configuration using (a) dedicated indoor system and (b) outdoor-to-indoor repeater.

too small, a mobile near an antenna may cause excess interference in the uplink direction due to too high minimum transmission power. A typical minimum value for coupling loss is approximately 50 dB, calculated based on a minimum mobile transmission power of −50 dBm and a receiver sensitivity of −100 dBm. Practical issues concerning the basics of indoor DAS design are well covered in literature (see, for example, [21]).

12.5.1.1 Indoor Propagation Prediction

To have reliable calculations for indoor propagation (in, for example, a planning tool), propagation models for indoor environment are needed. The indoor environment is challenging for propagation prediction. Even so, there are several propagation models available. The models are divided into empirical models (e.g., COST-231 multi-wall model, Ericsson model) and deterministic models (e.g., ray tracing) [14,20]. The simplest empirical models only model the propagation slope for different indoor environments; thus, the accuracy is very poor. Empirical wall and floor factor models have a distance-dependent free space loss component, where losses caused by wall and floor penetration are added. Empirical models for the indoors utilize ray tracing techniques, which have good theoretical accuracy but require high computation power. However, they also require very accurate information about the building, and moved furniture or an opened door may have a significant impact on the results, and thus errors are expected in practice. There are different commercial tools available where the building layout can be uploaded. After defining the materials and setting the antenna position and EIRP values in the tool, coverage estimation is calculated. Currently, indoor propagation estimation is primarily based on empirical models, where low accuracy requires field measurements to verify the results.

12.5.2 Planning of Outdoor-to-Indoor Repeater System

The key parameter that defines the repeater performance is the repeater amplifier gain. The required repeater amplifier gain value to achieve a certain received DL signal strength at the repeater output port naturally depends on the donor link properties of the outdoor-to-indoor repeater, that is, the losses and gains in the donor link path. The main contributor in donor link loss is the free space attenuation due to distance between the repeater donor antenna and the mother base station antenna. In addition, the antenna line components of the donor base station and the donor antenna line of the repeater contribute to the total loss. Furthermore, to achieve a certain signal strength (EIRP) at the indoor antenna, the losses caused by the serving indoor antenna system (either single antenna or DAS) must also be considered. The boundary values limiting the acceptable

repeater amplifier gain are maximum allowed noise rise at UL receiver, repeater antenna isolation, and maximum repeater output power.

Because a repeater is merely an amplifier, noise is amplified together with the desired signal at the repeater. Due to amplification of noise at repeater, the receivers affected by the repeater will experience increased noise levels, when the repeater is turned on (even with no traffic in the network). Increased received noise power at the base station directly leads to decreased base station sensitivity. In the uplink direction, the impact of repeater noise is more significant due to low coupling loss on the donor side (line-of-sight connection and two highly directive BS antennas used). In the downlink, the mobile station receiver typically has lower sensitivity, and the mobile antenna can be described as an omnidirectional antenna. Moreover, in the uplink direction, the receiver at the base station is shared by all mobile stations in the cell, and thereby the repeater directly affects the performance of the entire macro cell. Due to the noise-related phenomena described above, the total repeater performance is typically a compromise between increased repeater service area and decreased mother cell performance in the uplink. Hence, both the uplink and downlink must be considered in outdoor-to-indoor repeater planning. The mathematical presentation of the noise and sensitivity behavior in analog repeater systems can be found in [18].

A narrow beam repeater donor antenna is typically preferred to direct and gather the signal energy toward and from the mother cell antenna. Due to the narrow beam, low angular spread and thus line-of-sight between the repeater donor antenna and the mother cell antenna are typically required in order to be able to pick up the energy of the desired signal. When selecting the donor link configuration (i.e., donor antenna type and direction), emphasis should be placed on establishing high cell isolation. The cell isolation here means that the difference in the received signal levels from the first and second best cells at the donor antenna location is high enough to avoid amplifying an excess amount of other cell interference using the repeater. The impacts of donor cell isolation on system performance are discussed in more detail in [9]. If the two macro cells are repeated with almost equal level, all users in the repeater service area will be in soft handover, thereby wasting resources from the participating cells. Usually it can be assumed that the donor link connection has line-of-sight to the mother cell. Thus, to increase cell isolation, accurate antenna directioning and narrow beam antennas are preferred to separate the desired mother cell signal from the other interfering cells.

12.5.3 Handover Functionality

The fundamental difference in the functionality between a dedicated indoor system and an outdoor-to-indoor repeater is the handover operation when

users are moving from outdoors to indoors, and vice versa. The difference can be assessed by considering a situation where a user of the network is approaching the planned indoor location (i.e., building) with an active HSDPA packet data connection. In the case of a dedicated indoor system, the user must be handed over from the current outdoor macro cell to the new indoor cell while entering the building. Here, the importance of proper indoor planning is emphasized. Users must be seamlessly and successfully handed over to the indoor cell. If the handover area between the outdoor macro cell and the indoor cell is poorly planned, unnecessary handovers from and to the indoor cell may occur.

The handover operation with outdoor-to-indoor repeater is different compared to the dedicated indoor system. Because the indoor coverage produced by the repeater originates from the same logical cell, that is, from the outdoor mother cell (assuming that the building is located in a cell dominance area rather than cell edge), no handovers are required. The mobile station only experiences a sudden increase in the received signal strength when the mobile station moves into the building and becomes served by the indoor antennas. Thus, the utilization of outdoor-to-indoor repeaters also reduces the amount of required signaling load in the cell. However, the correct repeater planning is emphasized here, in particular to ensure the proper operation of the surrounding macrocellular network. The difference in handover functionality of the two indoor implementation approaches is visualized in Figure 12.4.

12.5.4 HSDPA Indoor Link Budget

The fundamental tools of coverage planning are link budget (also called power budget) and propagation model. The outputs of a link budget calculation are the maximum allowed path losses in the uplink and downlink directions. With a proper propagation model, the maximum coverage in decibels can be converted to maximum distance in meters when the propagation environment is known. Example link budgets for outdoor macrocellular WCDMA/UMTS Release 99 configuration can be found from the literature (e.g., [6,12,13]). Therefore, the link budget discussion here focuses on the HSDPA indoor configuration.

In Table 12.4, link budget for dedicated indoor systems using UMTS R99 384-kbps service, Table 12.3, UMTS R5 HSDPA service, and also Table 2.4, UMTS HSDPA R5 outdoor-to-indoor repeater configuration are shown[1]. In HSDPA link budgets, the uplink service is planned to provide sufficient capacity for HSDPA uplink feedback information. The link budgets are only

[1] The example link budget can be downloaded in Excel format from http://www.cs.tut.fi/tlt/RNG/IndoorLinkBudget.xls.

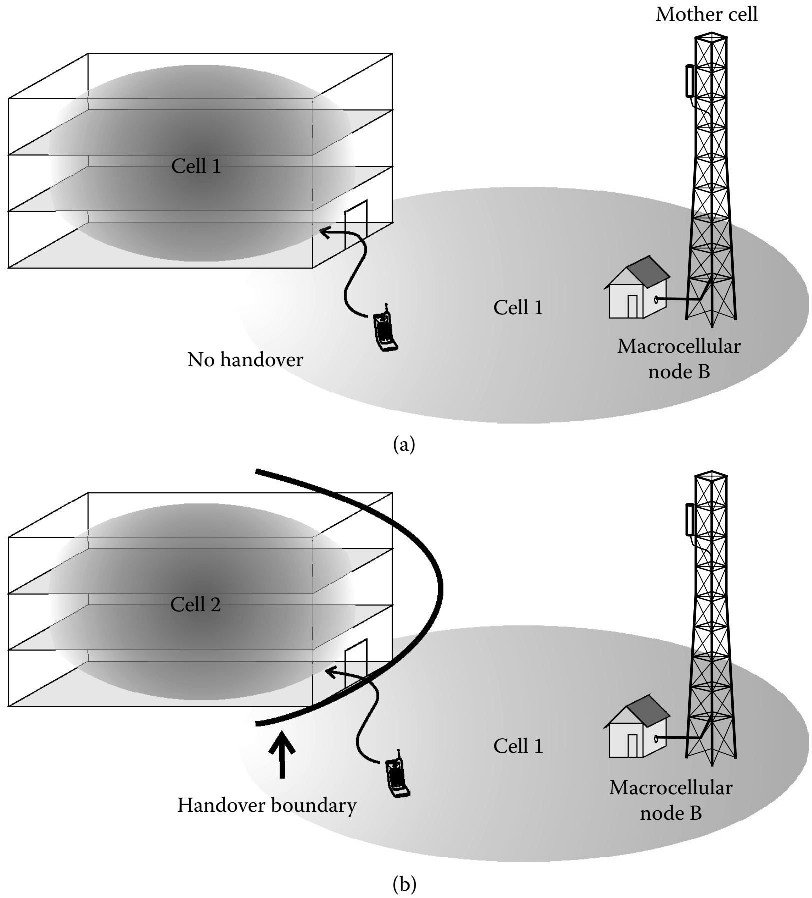

Figure 12.4 Difference in handover functionality of (a) outdoor-to-indoor repeater and (b) dedicated indoor system.

examples, and the actual link budget must always be done carefully to match each network implementation. All the details of the link budget calculations are not shown here, but can be found in literature (e.g., [6,12,13]). The link budget is divided to general parameters, service profile, receiving end, and transmitting end. For the outdoor-to-indoor repeater configuration, repeater parameters are introduced.

12.5.4.1 General Parameters and Service Profile

The general parameters include the fundamentals of the radio interface, and are the same for each configuration. In the service profile, the network load is the upper limit before load control and admission control functions start to limit connections. Here the load is fixed to 50%, but to get more accurate

Table 12.2 Link Budget for UMTS R99 Indoor, 384-kbps Service

Parameter	*Unit*	*Value*	
General parameters		*Uplink*	Downlink
Chip rate	cps	$3.84.10^{6}$	
Noise bandwidth ($\alpha = 1.22$)	Hz	$4.68.10^{6}$	
Temperature	K	293	
Boltzmann constant	J/K	$1.38.10^{-23}$	
Frequency	Mhz	1950	2150
Service profile	Unit	Uplink	Downlink
Load	%	50	50
Required bit rate (phy layer)	kbps	480	480
Spreading factor		4	8
Receiving end		NodeB	Mobile
Noise figure	dB	4	8
Noise power	dBm	−103.2	−99.2
Interference margin	dB	3.0	3.0
Total interference level	dBm	−100.2	−96.2
Required Eb/N0	dB	4	7
Processing gain	dB	6.0	9.0
Antenna diversity gain	dB	0	0
SHO diversity gain	dB	1	2
Power control headroom	dB	3	0
Required C/I	dB	0.0	−4.0
Receiver sensitivity	dBm	−100.2	−100.3
RX antenna gain	dBi	7	0
LNA gain	dB	0	0
DAS antenna line losses	dB	30	0
Required signal power	dBm	−77.2	−100.3
Transmitting end		Mobile	NodeB
Indoor Node B total power	W		8
Indoor Node B total power	dBm		39.0
TX Power / connection	W	0.13	0.8
TX Power / connection	dBm	21.0	29.0
Antenna gain	dBi	0	7
DAS antenna line losses	dB	0	30
Peak EIRP	dBm	21.0	6.0
Maximum path loss	dB	98.2	106.3

Table 12.3 Link Budget for UMTS HSDPA R5 Indoor

Parameter	*Unit*	*Value*	
General parameters		*Uplink*	*Downlink*
Chip rate	cps	$3.84.10^6$	
Noise bandwidth ($\alpha = 1.22$)	Hz	$4.68.10^6$	
Temperature	K	293	
Boltzmann constant	J/K	$1.38.10^{-23}$	
Frequency	Mhz	1950	2150
Service profile	Unit	Uplink	Downlink
Load	%	50	50
Number of HS-DSCH codes			10
Required bit rate (phy layer)	kbps	240	2000
Spreading factor		8	16
Receiving end		NodeB	Mobile
Noise figure	dB	4	8
Noise power	dBm	−103.2	−99.2
Interference margin	dB	3.0	3.0
Total interference level	dBm	−100.2	−96.2
Required Eb/N0 (UL) / SINR (DL) [1]	dB	4	13
Processing gain	dB	9.0	12.0
Antenna diversity gain	dB	0	0
SHO diversity gain	dB	1	0
Power control headroom	dB	3	0
Required C/I	dB	−3.0	1.0
Receiver sensitivity	dBm	−103.3	−95.3
RX antenna gain	dBi	7	0
LNA gain	dB	0	0
DAS antenna line losses	dB	30	0
Required signal power	dBm	−80.3	−95.3
Transmitting end		Mobile	NodeB
Indoor Node B total power	W		8
Indoor Node B total power	dBm		39.0
HS-DSCH Power	W	0.13	5
HS-DSCH Power	dBm	24.0	37.0
Antenna gain	dBi	0	7
DAS antenna line losses	dB	0	30
Peak EIRP	dBm	24.0	14.0
Maximum path loss	dB	104.3	109.3

Table 12.4 Link Budget for UMTS HSDPA Outdoor-to-Indoor Repeater

Parameter	*Unit*	*Value*	
General parameters		*Uplink*	*Downlink*
Chip rate	cps	$3.84.10^{6}$	
Noise bandwidth ($\alpha = 1.22$)	Hz	$4.68.10^{6}$	
Temperature	K	293	
Boltzmann constant	J/K	$1.38.10^{-23}$	
Carrier frequency	Mhz	1950	2150
Service profile	Unit	Uplink	Downlink
Load	%	50	50
Number of HS-DSCH codes			10
Required bit rate (phy layer)	kbps	240	2000
Spreading factor		8	16
Repeater parameters	Unit	Uplink	Downlink
Repeater noise figure	dB	3	3
Repeater donor link loss (FSL)	dB	100	100
Repeater donor antenna gain	dBi	18	18
Repeater donor antenna line loss	dB	4	4
Repeater amplifier gain	dB	66.2	66.2
Repeater system gain	dB	–19.9	–19.9
Receiving end		NodeB	Mobile
Noise figure	dB	4	8
Effective noise figure with repeater	dB	5.0	8.0
Noise power	dBm	–102.2	–99.2
Interference margin	dB	3.0	3.0
Total interference level	dBm	–99.2	–96.2
Required Eb/N0 (UL) / SINR (DL) [1]	dB	4	13
Processing gain	dB	9.0	12.0
Antenna diversity gain	dB	0	0
SHO diversity gain	dB	1	0
Power control headroom	dB	3	0
Required C/I	dB	–3.0	1.0
Receiver sensitivity	dBm	–102.2	–95.3
Outdoor Node B antenna line loss	dB	0	
Outdoor Node B antenna gain	dBi	15	
Repeater system gain	dB	–19.85	
RX antenna gain	dBi	7	0
Outdoor Node B LNA gain	dB	0	0
DAS antenna line losses	dB	30	0
Required signal power	dBm	–74.4	–95.3

Table 12.4 Link Budget for UMTS HSDPA Outdoor-to-Indoor Repeater (Continued)

Parameter	*Unit*	*Value*	
General parameters		*Uplink*	*Downlink*
Transmitting end		Mobile	NodeB
Outdoor Node B total power	W		20
Outdoor Node B total power	dBm		43.0
Tx Power / HS-DSCH Power	W	0.13	8
Tx Power / HS-DSCH Power	dBm	24.0	39.0
Outdoor Node B antenna line loss	dB		0
Outdoor Node B antenna gain	dBi		15
Repeater system gain	dB		−19.9
Antenna gain	dBi	0	7
DAS antenna line losses	dB	0	30
Peak EIRP	dBm	24.0	11.2
Maximum path loss	dB	98.4	106.4

results, the actual load of the HSDPA cell should be calculated based on High-Speed Downlink Shared Channel (HS-DSCH) signal-to-interference-plus-noise ratio (SINR) (see Equation (12.2)), inter-cell interference, and network geometry factor [7]. Either a physical layer bit rate or a spreading factor is needed to calculate processing gain (PG). For R99, the used bit rates are the maximum available. In HSDPA, the bit rate changes every 2 ms due to adaptive modulation and coding. Therefore, the bit rate in the link budgets is an adjustable average target value for which the maximum path loss is calculated.

12.5.4.2 Receiving and Transmitting Ends

In the receiving end, the noise figures are typical values for UE and Node B. The noise power equals the thermal noise on the system noise bandwidth plus receiver noise figure. After calculating the interference margin from the cell load level, the total interference level at the receiver can be calculated.

The required signal level divided by the noise plus interference level is called E_b/N_0, which depends on several variables [13]; and therefore, only estimates can be given. Because for HSDPA connections the bit rate is changing every 2 ms, a single E_b/N_0 requirement cannot be given. However, the HSDPA bit rate with a certain number of codes can be connected to a certain SINR. The value in the link budget is based on the simulations in [7], with ten codes. In indoor systems, diversity reception is not typically used. Also, the HSDPA connection does not support SHO or power control; thus, for HSDPA, the required carrier-to-interference ratio (C/I) is simply SINR − PG. Receiver sensitivity is equal to total interference level plus required C/I.

The impact of antenna line elements is added to the receiver sensitivity to obtain the required signal power at the receiver antenna. The Node B antenna line parameters are based on the example DAS shown in Figure 12.3(a). At the UE, the antenna is typically approximated as isotropic, and the antenna line losses are close to zero. The power settings are typical for indoor Node B. The maximum transmission power for R99 UE is +21 dBm; and for HSDPA UE, it is +24 dBm [2]. After calculating the EIRP at the transmitter antenna, the maximum path loss can be calculated.

12.5.4.3 Repeater

Some changes exist in the link budget for the outdoor-to-indoor repeater configuration, when compared to the link budget for the dedicated indoor system. The selected values for the donor antenna line loss and repeater noise figure correspond to typical ones in the situations where a repeater is deployed to a macrocellular network. The values for donor link loss and donor antenna type are very case specific, but here a donor link loss of 100 dB and an antenna of 18 dBi gain has been selected[2]. Furthermore, macro cell antennas that have relatively narrow horizontal beam width (30° half-power beam width) typically have a gain value near 18 dBi.

To take into account the increased noise level at the base station receiver, a modified noise level value has been added to the link budget for the outdoor-to-indoor repeater case. The effective noise figure of the base station receiver is calculated based on the repeater link properties (gains and losses) according to the approach presented in [18]. The modified noise level value has a direct impact on the sensitivity level of the receiver and thus on the required signal power in the uplink direction of the link budget. A practical guideline for selecting the repeater amplifier gain is a value such that the noise level in the base station receiver has increased 1 dB from the original level after deploying the repeater. An increase of 1 dB can be considered acceptable. The repeater system gain is equal to the combined gain from the components in the repeater donor antenna line, donor link loss, and repeater amplifier gain.

12.5.4.4 Maximum Path Loss

The maximum allowed path loss is the difference between the required signal power and the EIRP calculated separately for both directions. It is worth noting that the planning margins, such as body loss, slow fading, etc., are not included in the link budget, but must be taken into account in the actual planning. Based on the calculated link budgets, very similar downlink maximum path loss is observed with outdoor-to-indoor repeater

[2] Free space attenuation of 100 dB is equal to a distance of about 1100 m.

implementation and with dedicated indoor systems. These maximum path loss values also correspond quite well to the maximum path loss for R99 indoor packet data service (Table 12.4), and the difference with respect to the indoor HSDPA system is approximately 3 dB in downlink and 6 dB in uplink direction. Thus, note how nearly equal coverage can be achieved using the outdoor-to-indoor repeater or dedicated indoor system. However, it should be emphasized that the behavior of the two systems in case of increasing load is different. While a dedicated indoor system provides additional radio resources for indoor users, in the outdoor-to-indoor repeater approach, the radio resources available for the indoor users are shared between the indoor users and the outdoor mother cell users. Thus, the repeater only helps the network utilize the free existing radio resources by amplifying the signal rather than providing new resources. Because the availability of radio resources of the dedicated indoor system are independent of the surrounding cells, clearly higher maximum capacity can be achieved using the dedicated indoor system—when compared to the repeater approach.

12.5.5 HSDPA Coverage and Capacity

Due to adaptive behavior, the coverage and capacity in HSDPA are even more strongly connected together than in traditional WCDMA planning. The link budget calculation (previous subsection) gives some indication of coverage requirements. A deeper understanding of HSDPA indoor performance requires system simulations and field measurements. In the radio interface, the instantaneous SINR of HS-DSCH is fundamentally defining the achievable HSDPA throughput. Thus, planning should be targeted at maximizing the SINR in the network.

The instantaneous SINR of HS-DSCH channel can be calculated:

$$SINR = SF_{16}\frac{P_{HS\text{-}DSCH}}{(1-\alpha)P_{own} + P_{other} + P_{noise}} \tag{12.2}$$

where SF_{16} is spreading factor of 16, $P_{HS\text{-}DSCH}$ is the total HSDPA power in own cell, α is the code orthogonality, P_{own} is the total power from own cell, P_{other} is the total power from all neighboring cells, and P_{noise} is the thermal noise power [7]. All the powers are received powers; thus, the corresponding link losses must be taken into account if the calculation is based on transmitted power.

In addition to the parameters in Equation (12.2), the achieved throughput with certain SINR depends on the propagation environment, system capabilities, and system parameters. The maximum number of HS-DSCH codes that a receiver at mobile can handle is 5, 10, or 15, depending on the mobile category [2,3] and the maximum available throughput is 3.6, 7.2, or 10.8 Mbps, respectively. The number of errors and retransmissions,

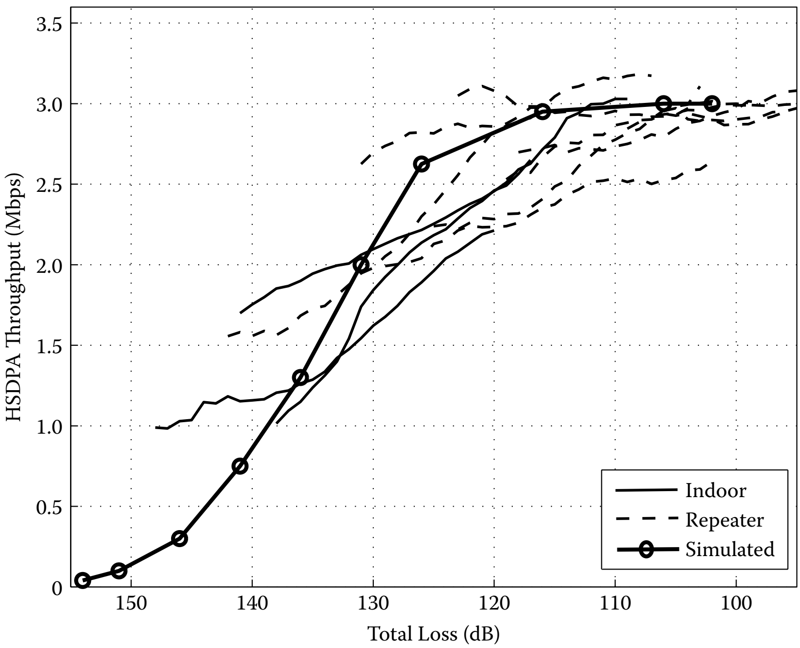

Figure 12.5 Measured [9] and simulated [7] single-user throughput values as a function of total path loss. HSDPA with five codes, 5-W power allocation.

as well as handling of retransmitted data, also affect the achieved throughput. The practical throughput can, of course, be further limited by other system-related issues, such as bottlenecks in different interfaces or lack of processing capacity in system elements.

In Figure 12.5, HSDPA throughput as a function of total path loss for single user with five codes and 5 W power allocation is plotted. The total path loss consists of antenna line losses and air interface path loss. The simulation-based values adopted from [7] are averaged between 3 W and 7 W power allocation, for Pedestrian-A channel (outdoor). The measured values are gathered from [9], where the path loss estimation is based on received signal code power (RSCP) measurements that are made with a commercial HSDPA UE (category 5/6 [2]) connected to a field measurement tool [17]; thus, some errors are expected due to calibration error and low time resolution. The measurements were made with a single user in a dedicated indoor system and outdoor-to-indoor repeater configurations, both connected to a distributed antenna system in different indoor environments.

The simulated curve in Figure 12.5 shows the expected throughput, and the measured values can be compared with reasonable accuracy. The

graph shows that both the dedicated indoor system and outdoor-to-indoor repeater are able to operate as expected based on the simulations. It is also worth noting that it is possible to get high throughput with 16QAM modulation via repeater link (QPSK modulation with five codes can provide maximum 1.8 Mbps of throughput). Thus, outdoor-to-indoor repeating is a feasible solution for improving HSDPA indoor coverage.

Measurements for a UMTS indoor system with different antenna configurations in different indoor environments are presented, for example, in [8,9]. The results show that it is beneficial to increase the antenna density—that is, to decrease the average antenna spacing in DAS—by splitting the signal into several antennas. Higher antenna density provides smoother signal coverage and better signal level, finally leading to better HSDPA performance. Increasing the antenna density from 1 to 3 antennas at 50 m measurement route improved the pilot coverage in the range of 1 and 5 dB, and HSDPA throughput in the range of 5% and 30%. A radiating cable configuration was also tested, and it was observed to provide very smooth coverage close to the cable, but the signal level compared to discrete antennas was low even close to the cable. Keeping the signal level above coverage threshold requires a dense network of radiating cables installed close to user locations. Thus, discrete antennas outperform radiating cable solutions in terms of coverage and implementation complexity.

Furthermore, pilot coverage planning thresholds for indoor environments to achieve certain average throughput are presented in, for example, [9]. The throughput values are applicable for HSDPA with five codes. With typical P-CPICH and HSDPA power settings for indoor environments, a pilot coverage threshold of −50 dBm was measured, to provide average throughput of 3 Mbps; a threshold of −80 dBm gave an average throughput of 2.5 Mbps; and for threshold below −80 dBm, the throughput was significantly decreased. Therefore, a pilot coverage threshold of −80 dBm can be recommended for indoor planning. Figure 12.5 can be further used to estimate throughput thresholds for the total path loss.

In Figure 12.6, a measurement example of HSDPA with ten codes in an indoor environment is shown. The RSCP of a pilot channel and HSDPA throughput are plotted as a function of time. The measurement starts below an antenna, and ends when the HSDPA connection breaks due to low coverage. The measurement was taken in a long office corridor. Close to the antenna (about 40 seconds from the beginning), the received signal level was high enough to achieve maximum throughput almost constantly. After that point in time, maximum throughput cannot be achieved, but yet remains at a very good level. The first part (75 seconds from the beginning) of the measurement route is partly line-of-sight, and the quick drop after that is partly caused by going behind a corner to a non-line-of-sight environment. The example measurement emphasizes the importance of good coverage if high throughput values are required.

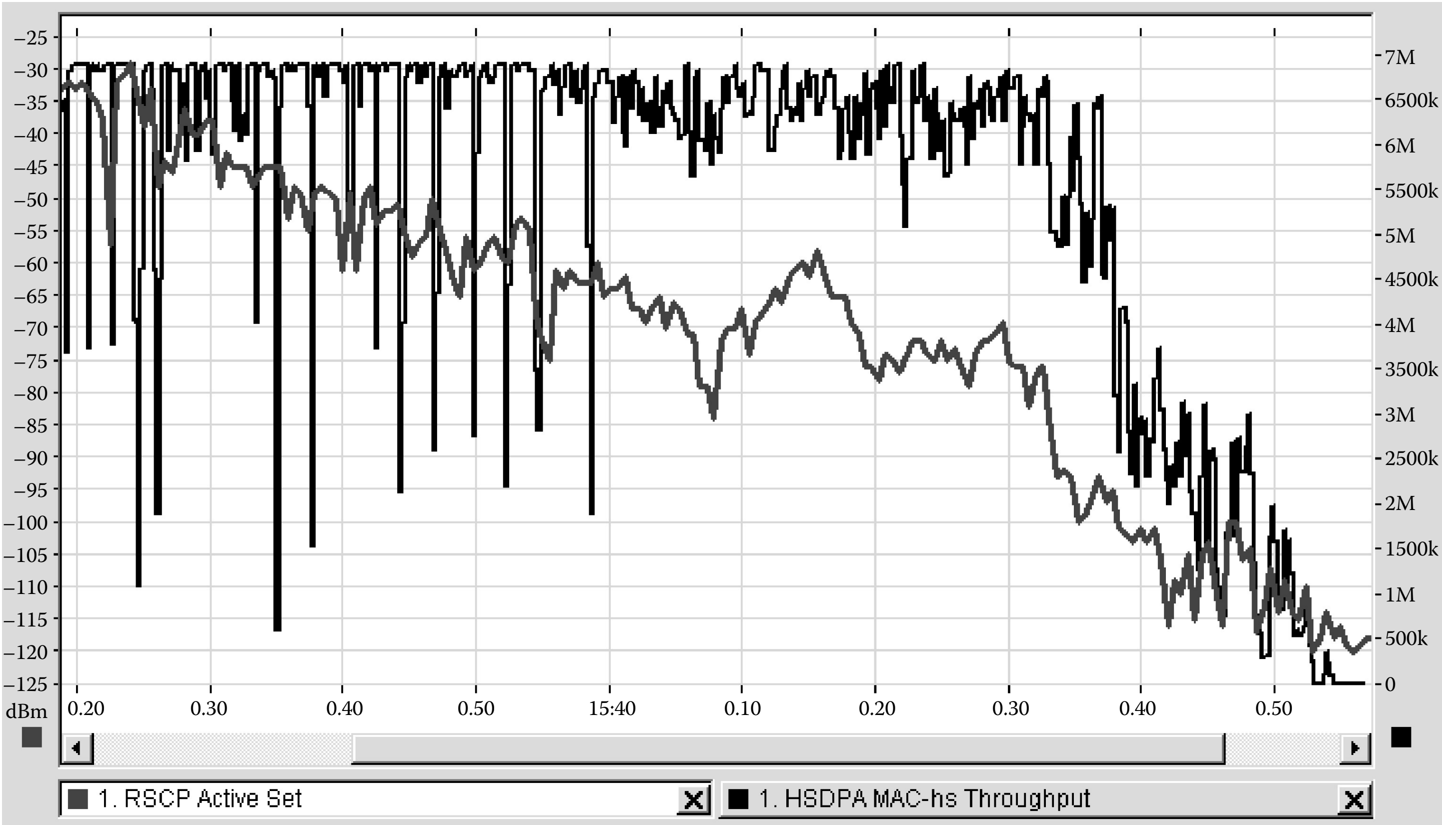

Figure 12.6 Achieved HSDPA throughput and pilot channel received power as a function of time for HSDPA with ten codes. Example for single user, measured from below the antenna to the cell edge in an indoor environment.

12.5.6 Quality of Planning

The quality of planning defines the capability of the network to function properly when it is utilized with full capacity, as well as the capability to provide sufficient coverage over the entire network area. As discussed previously, with WCDMA and HSDPA, coverage and capacity are tied together. Thus, the available capacity is defined by comparing the desired signal power levels to the noise and interference power levels, e.g. as in Equation (12.2) for HSDPA. Therefore, a common planning target of all cellular WCDMA-based systems is to minimize the interference between the cells.

The effect of surrounding macro cells must be considered to prevent interference from penetrate inside the building. Correspondingly, high-quality indoor planning guarantees that no interference is caused to the surrounding macro cells from the indoor antennas. The high quality can be maintained by proper transmission power and indoor antenna configuration for the dedicated indoor system. In case of an outdoor-to-indoor repeater, interference in the indoor location is also produced by the macrocellular outdoor network when the signals are amplified by the repeater. However, orthogonality between the codes of the mother cell users should be relatively good due to line-of-sight propagation from the macro cell to the repeater. Also, careful coverage planning is important for efficient indoor HSDPA operation. Sufficient coverage must be provided over the entire network area, which should always be verified by field measurements. Furthermore, the quality of coverage can be improved by optimizing the antenna configuration, for example, by increasing the antenna density in DAS to enhance HSDPA throughput.

References

[1] 3GPP Technical Recommendation 25.956 V6.0.0 , Release 6. Universal Terrestrial Radio Access (UTRA); repeater planning guidelines and system analysis.
[2] 3GPP Technical Specification, TS 25.306, Version 5.9.0, Release 5. UE Radio Access Capabilities Definition.
[3] 3GPP Technical Specification, TS 25.308, Version 5.7.0, Release 5. High Speed Downlink Packet Access (HSDPA); Overall description; Stage 2.
[4] E. Dahlman, S. Parkvall, J. Sköld, and P. Beming. *3G Evolution: HSPA and LTE for Mobile Broadband*. Academic Press, 2007.
[5] H. Hashemi. The indoor radio propagation channel. In *Proceedings of the IEEE*, 81: 943–968, September 1993.
[6] H. Holma and A. Toskala, Editors. *WCDMA for UMTS*. John Wiley & Sons Ltd., 2000.
[7] H. Holma and A. Toskala, Editors. *HSDPA / HSUPA for UMTS*. John Wiley & Sons Ltd., 2006.

[8] T. Isotalo, J. Lempiäinen, and J. Niemelä. Indoor planning for high speed downlink packet access in WCDMA cellular network. *Wireless Personal Communications Journal*, 52(1): 89–104, 2010.

[9] T. Isotalo, P. Lähdekorpi, and J. Lempiäinen. Improving HSDPA indoor coverage and throughput by repeater and dedicated indoor system. *EURASIP Journal on Wireless Commun. Networking*, April 2009. In press.

[10] K. Hiltunen, B. Olin, and M. Lundevall. Using dedicated in-building systems to improve HSDPA indoor coverage and capacity. In *IEEE 61st Vehicular Technology Conference, VTC 2005-Spring*, pp. 2379–2383, 2005.

[11] Kathrein. http://www.kathrein.de, 2009.

[12] J. Laiho, A. Wacker, and T. Novosad, Editors. *Radio Network Planning and Optimisation for UMTS*. John Wiley & Sons Ltd., 2002.

[13] J. Lempiäinen and M. Manninen, Editors. *UMTS Radio Network Planning, Optimization and QoS Management*. Kluwer Academic Publishers, 2003.

[14] M.J. Nawrocki, M. Dohler, and A.H. Aghvami, Editors. *Understanding UMTS Radio Network Modelling, Planning and Automated Optimisation*. John Wiley & Sons, Ltd., 2008.

[15] M.K. Simon and M.S. Alouini. Digital Communications over Fading Channels: A Unified Approach to Performance Analysis. Wiley InterScience, Sep 2000.

[16] K. Pedersen and P. Mogensen. The downlink orthogonality factors influence on WCDMA system performance. In *IEEE 56th Vehicular Technol. Conf. VTC 2002-Fall*, pp. 2061–2065, 2002.

[17] Anite plc. Anite Nemo Outdoor Product description. http://www.anite.com/nemo/, March 2009.

[18] R. Anderson, B. Arend, and K. Baker. Power Controlled Repeaters for Indoor CDMA Networks. In White paper, Qualcomm Inc., 2003.

[19] Radio Frequency Systems (RFS). http://www.rfsworld.com, 2009.

[20] S.R. Saunders. *Antennas and Propagation for Wireless Communication Systems*. John Wiley & Sons, Ltd., 1999.

[21] M. Tolstrup. *Indoor Radio Planning*. John Wiley & Sons, Ltd., 2008.